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THE STRUCTURE OF EVAPORATING AND COMBUSTING SPRAYS:
MEASUREMENTS AND PREDICTIONS

Semi-Annual Status Report

For the Period

September 1, 1982 to February 28, 1983

by

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NOMENCLATURE

<u>Symbol</u>	<u>Description</u>
a	acceleration of gravity
c	particle concentration
c_D	drag coefficient
c_i	parameters in turbulence model
c_p	specific heat
d	injector diameter
d_p	drop diameter
D	binary diffusivity
$e_{b\lambda}$	monochromatic blackbody emissive power
f	mixture fraction
g	square of mixture fraction fluctuations
G	particle mass flux
h	heat transfer coefficient
h_s, h_p	enthalpy
H	total enthalpy
I_λ	monochromatic radiation intensity
K_λ	monochromatic absorption coefficient
k	turbulence kinetic energy
L_e	dissipation length scale
m	drop mass
\dot{m}	drop evaporation rate
\dot{m}_o	injector flow rate
\dot{M}_o	injector thrust
\dot{n}_i	number of drops per unit time in class i

<u>Symbol</u>	<u>Description</u>
$P(f)$	probability density function of f
Pr	Prandtl number
Re	Reynolds number
r	radial distance
s	distance along beam path
Sc	Schmidt number
S_ϕ	source term
$S_{d\phi}$	droplet source term
t	time
t_e	eddy lifetime
t_t	drop transit time
T	gas temperature
T_p	drop temperature
u	axial velocity
\vec{u}_p	drop velocity vector
v	radial velocity
v^o	Favre radial velocity
x	axial distance
\vec{x}_p	drop position vector
y^2	variance of radial particle position
Y_i	mass fraction of species i
α	weighting factor, Eq. (6)
ϵ	rate of dissipation of turbulence kinetic energy
λ	thermal conductivity
μ_t	turbulent viscosity
ρ	density

<u>Symbol</u>	<u>Description</u>
τ	particle relaxation time
σ_i	turbulent Prandtl/Schmidt number
ϕ	generic property

Subscripts

c	centerline quantity
f	liquid
g	vapor
p	drop property
s	drop surface
0	injector exit condition
∞	ambient condition

Superscripts

()'	fluctuating quantity
(̄)	time mean value

Semi-Annual Status Report
September 1, 1982 to February 28, 1983
The Structure of Evaporating and Combusting Sprays:
Measurements and Predictions

SUMMARY

This report describes progress on an investigation of spray structure for the semi-annual period--September 1, 1982 to February 28, 1983. The objective of the work is to complete new measurements of the structure of particle-laden jets and nonevaporating and evaporating sprays in order to evaluate models of these processes. Model evaluation is also being initiated-- considering methods developed during earlier NASA-sponsored research in this laboratory as well as a new stochastic approach developed during this investigation.

Work during this report period concentrated on experimental aspects of the investigation. Measurements were completed in particle-laden jets, to supplement existing results in the literature. This included mean and fluctuating velocities of both phases, particle mass fluxes, calibration of particle drag properties, and measurements of particle size distributions (which were very nearly monodisperse for three particle sizes and several particle loadings). Particular attention was given to defining initial conditions of these flows, since the absence of this information was a major limitation when using existing results for definitive model evaluation.

Experiments were also completed to provide mean and fluctuating gas velocities, mean mixture fraction, and drop size distributions in two evaporating sprays having differing initial Sauter mean diameters. These results supplement similar measurements in nonevaporating sprays completed during the first year of this investigation.

In order to complete evaluation of the models for the sprays, information on initial drop size and velocities are needed. A multi-flash photography apparatus was developed to provide reliable measurements of these properties. This arrangement was successfully evaluated in the particle-laden jets and is currently being employed for spray measurements.

Three models of the process are being evaluated: (1) a locally homogeneous flow (LHF) model, where slip between the phases is neglected and the flow is assumed to be in local thermodynamic equilibrium; (2) a deterministic separated flow (DSF) model, where slip and finite interphase transport rates are considered but effects of particle/drop dispersion by turbulence and effects of turbulence on interphase transport rates are ignored; and (3) a stochastic separated flow (SSF) model, where effects of interphase slip, turbulent dispersion and turbulent fluctuations are considered using random sampling for turbulence properties in conjunction with random-walk computations for particle motion. All three models use a k-e-g turbulence model, which was extensively evaluated for single-phase flows, during earlier work in this laboratory.

Computations during this report period were limited to evaluation of the LHF model for evaporating sprays. Findings were similar to earlier

results with this model for nonevaporating sprays, e.g., predictions were only qualitatively correct due to overestimation of interphase transport rates and effects of enhanced turbulent dispersion of drops.

Current work involves completing size and velocity measurements for the drop phases, in both the nonevaporating and evaporating sprays, to facilitate evaluation of the separated flow models. Computations are also in progress to complete comparison between predictions and measurements for all experimental flows and theoretical models considered during the investigation.

1. Introduction

The potential value of rational design procedures for liquid-fueled combustors has motivated extensive efforts to develop reliable models of spray evaporation and combustion processes. The goal is to reduce the time and cost of cut-and-try methods of development by providing a better understanding of fundamental spray processes and methods for estimating the effect of specific design changes. While numerous models of sprays have been proposed, cf. Ref. 1 for a number of examples, there are few well-defined measurements in sprays to evaluate model predictions. In view of this, these models have not received significant application as design tools. The primary objective of the present investigation is to provide experimental results concerning spray structure in order to help fill this gap in the literature. The new data is also being used to evaluate typical models of multiphase flows--considering methods representative of recent spray models.

The investigation is considering noncombusting flows in order to provide adequate background for future studies of combusting sprays. In order to simplify both measurements and computations for evaluation of spray models, a simple steady axisymmetric flow configuration is being examined, involving flows injected into a stagnant air environment. The experiments are being undertaken in a systematic manner, to develop both theoretical and experimental techniques, considering the following flows in turn:

- (1) Isothermal Air Jet--used to check experimental techniques.
- (2) Particle-Laden Jets--to provide a test of turbulent particle dispersion effects.
- (3) Non-Evaporating Sprays--to provide a test of drop coalescence effects as well as high particle density flows.
- (4) Evaporating Sprays--to provide a test of drop heat and mass transfer phenomena.

Each of these flows involves careful characterization of initial conditions, since this was a major deficiency of past experimental studies. The new structure measurements include: mean and fluctuating gas velocities; mean particle fluxes; particle sizes and velocities; mean temperature; and mean concentration of gaseous species (to the extent that each measurement is appropriate for a particular flow). Experimental

methods emphasize non-intrusive methods such as laser-Doppler anemometry, Fraunhofer diffraction, and multi-flash photography. Probes have been used, however, for drop size determinations, particle fluxes, temperatures, and species concentration measurements. Aside from multi-flash photography, experimental methods were largely established during past NASA-sponsored research in this laboratory.

Three models of the process are being evaluated: (1) a locally homogeneous flow (LHF) model, where slip between the phases is neglected and the flow is assumed to be in local thermodynamic equilibrium; (2) a deterministic separated flow (DSF) model, where slip and finite interphase transport rates are considered, but effects of particle/drop dispersion by turbulence--as well as effects of turbulence on interphase transport rates--are ignored; and (3) a stochastic separated flow (SSF) model, where effects of interphase slip, turbulent dispersion, and turbulent fluctuations are considered using random sampling for turbulence properties in conjunction with random-walk computations for particle motion. All three models use a $k-e-g$ turbulence model, which was extensively evaluated earlier in this laboratory with single-phase flows.

Work during the first year of the investigation is reported elsewhere [1-6] and will only briefly be described here. These activities included development of experimental apparatus, initial measurements for isothermal air jets and nonevaporating sprays, and the development of the theoretical models. Model evaluation was initiated using existing data for particle-laden jets as well as the new measurements for nonevaporating sprays. The LHF and DSF models did not provide very satisfactory predictions over this data base. The DSF model generally underestimated the rate of spread of the dispersed phase as a result of ignoring the effects of turbulent dispersion. The LHF model provided reasonably good predictions for flows containing tracer-like particles, but was unsatisfactory for most practical flows. In contrast to the other models, the SSF model provided reasonably good predictions over the data base. This result was very encouraging; however, definitive model evaluation was not possible due to uncertainties in the initial conditions throughout the data base used for evaluation.

The objective of the present phase of the investigation was to eliminate these deficiencies in model evaluation. Measurements were undertaken in particle-laden jets with careful consideration of initial conditions. Experiments continued with nonevaporating sprays, resulting in the development of a multi-flash drop size and velocity technique which is being used to more adequately define initial conditions in the sprays. Finally, measurements were also undertaken in evaporating sprays in order to test model capabilities for predicting interphase heat and mass transport rates as well as effects of density variations in the continuous phase. While the bulk of project effort was devoted to experiments during this report period, some computations were completed using the LHF model as a first step in model evaluation.

Activities during this report period are described in the following. The report begins with a description of theoretical and experimental methods. Results are then discussed considering representative findings for both particle-laden jets and sprays. The report concludes with a summary of current status and plans for the next report period.

2. Theoretical Methods

2.1 General Description

Three theoretical models of spray processes are being considered: (1) a locally homogeneous flow (LHF) model, where slip between the phases is neglected and the flow is assumed to be in local thermodynamic equilibrium; (2) a deterministic separated flow (DSF) model, where slip and finite interphase transport rates are considered but affects on particle/drop dispersion by turbulence and affects of turbulence on interphase transport rates are ignored; and (3) a stochastic separated flow (SSF) model, where affects of interphase slip, turbulent dispersion and turbulent fluctuations are considered using random sampling for turbulence properties in conjunction with random-walk computations for particle motion. All three models use a k-e-g turbulence model.

The theoretical models have been extensively described during earlier reports and papers emanating from this investigation [1-6] as well as earlier work in this laboratory [7-9]. Therefore, the models will only be described very briefly in the following in order to qualitatively indicate their features. Original references should be consulted for further details.

All models employ the widely adopted procedures of k-e-g turbulence models for the gas phase, since this approach has been thoroughly calibrated during earlier work in this laboratory [7-9]. Major assumptions for the gas phase are: exchange coefficients of all species and heat are the same, buoyancy only affects the mean flow, and kinetic energy and radiative heat losses are negligible. Affects of buoyancy and radiation heat losses are generally small in practical sprays; therefore treating these phenomena as perturbations is justified. Neglecting kinetic energy limits the model to low Mach number flows, which is appropriate for the test conditions to be examined as well as for most practical combustion chambers. The assumption of equal exchange coefficients is widely recognized as being acceptable for high Reynolds number turbulent flows typical of spray processes.

In order to ensure adequate numerical closure with reasonable computation costs, the model is limited to boundary-layer flows with no recirculation. The present test flows are axisymmetric with no swirl; therefore, the analysis is posed accordingly. The advantage of these conditions is that they correspond to cases where the turbulence models were developed and have high reliability.

2.2 Locally Homogeneous Flow Model

The governing equations for the LHF model are presented elsewhere [1-9]. The basic premise of this model is that rates of transport between phases are fast in comparison to the rate of development of the flow as a whole. This implies that all phases have the same velocity and temperature and that phase equilibrium is maintained at each point in the flow. Therefore, the LHF model implies that the process is mixing-controlled. The dispersed-phase must have infinitely small particle sizes for this model to be exact. In practice, the model yields reasonably good results

for finite size particles having diameters less than 10 microns [1].

Under the LHF approximation, the flow is equivalent to a single-phase flow and affects of the dispersed phase only appear in the representation of thermodynamic properties (temperature, density, enthalpy, etc.) and molecular transport properties (viscosity, thermoconductivity, etc.). The representation of these properties is generally called the state relationships for the flow. Finding state relationships for thermodynamic properties is relatively straightforward. This involves conventional adiabatic mixing or adiabatic flame calculations, with the local state of the mixture specified by the mixture fraction (the fraction of material at a point which originated at the injector). Methods used for these computations are described elsewhere [1-9]. This approach is frequently referred to the conserved-scalar method--which has been widely used in past computations for turbulent combusting flows [10].

The main advantage of the LHF model is that there are only a few empirical constants, which are specified from earlier measurements, and only routine equilibrium computations and simplified injector quantities are required. In view of its ease of use, the model has recently demonstrated good capabilities for predicting spray properties [1-9]. The main defect is that the rate of flow development is overestimated in the two-phase region. Nevertheless, potential users of spray models are likely to begin with a version of this type, since computations are no more difficult than for a single-phase flow. Therefore, it is desirable to evaluate its performance against the experiments.

2.3 Deterministic Separated Flow Model

The deterministic separated flow model adopts the main features of the LHF model, but only for the gas phase. The liquid phase is treated by solving the Lagrangian equations of motion for the drops and then computing source terms in the governing equations for the gas phase which result from interphase transport affects. This general procedure corresponds to the particle tracking or particle-source-in-cell methods used in most recent two-phase flow models. The approach is often called the discrete droplet model.

The main assumptions of the drop trajectory calculations are as follows: dilute spray with drop transport parameters equivalent to a single drop in an infinite environment; ambient conditions given by mean flow properties; negligible effect of turbulent fluctuations on drop transport rates; empirical treatment of drag and convection affects; quasisteady gas phase; negligible drop shattering and collisions; liquid surface in thermodynamic equilibrium; and negligible radiation, Dufour and Soret affects. These assumptions are common for most spray models--their justification is discussed elsewhere [1-2].

Due to the difficulty of completely modeling internal transport processes of drops, the analysis considers two limits: (1) the infinite liquid diffusivity approximation where all properties within the drop are assumed to be uniform at each instant of time; and (2) the negligible diffusivity or "onion skin" model where the drop surface adapts immediately to changes in local ambient conditions, while the bulk liquid remains at

its initial state. These cases bound the range exhibited by real drops in sprays.

Initial conditions for this model are defined at a position where drop size and velocity data can be obtained--usually about 50 injector diameters from the injector exit for present test conditions. Needed initial conditions are size, velocity and direction at various radial positions in the flow for the drops as well as velocities and turbulence properties of the continuous phase. At this position the drops are divided into n groups defined by their initial properties. Subsequent properties for each group are found by integrating governing conservation equations for momentum, energy, mass and velocity. During these computations, the properties of the continuous phase are taken to be mean properties found from the k-e-g model. The interaction between the liquid and gas phases yields additional source terms for the continuous phase. These terms are found by computing the net change of mass, momentum and energy of each drop class as it crosses a computational cell. This procedure allows for full interaction between the phases, which is vital for treating the near-injector region.

The gas-phase equations are solved in the same manner as the LHF model. The only change in this portion of the program involves addition of the new source terms. The particle motion equations are solved at the same time in a step-wise fashion, using a second-order finite difference algorithm.

2.4 Stochastic Separated Flow Model

The basic separated flow analysis considered in Section 2.3 only provides for deterministic trajectories of particle groups. In practical turbulent flows, however, particles are also dispersed by turbulent fluctuations. Furthermore, interphase transport rates are influenced by fluctuations in local flow properties. These effects are considered in the stochastic separated flow model described in this section. The approach used to handle turbulent particle dispersion adapts stochastic methods first proposed by Gosman and Ioannides [11]. A complete discussion of the method appears in Refs. 1-6.

The stochastic separated flow model involves computing the trajectories of a statistically significant sample of individual particles as they move away from the injector (or the initial condition) and encounter a random distribution of turbulent eddies. These computations are completed using Monte Carlo methods. The main elements of this approach are methods for specifying the properties of each eddy and for determining the time of interaction of a particular particle with a particular eddy. The k-e-g representation of turbulence is used in the SSF model to provide a convenient method for prescribing these properties.

Properties within a particular eddy are assumed to be uniform, but properties change in a random fashion from eddy to eddy. The computations for the continuous phase and the trajectory calculations are the same as the deterministic separated flow model. The main difference in the trajectory calculations is that mean-gas properties in these equations are replaced by the instantaneous properties of each eddy.

The properties of each eddy are found at the start of interaction by making a random selection from the probability density function of velocity and mixture fraction. The velocity fluctuations are assumed to be isotropic with a Gaussian probability density distribution having a standard deviation obtained from the turbulence kinetic energy computed in the k-e-g model. The cumulative distribution function for the three velocity components is formed and each distribution is randomly sampled. This involves selecting three numbers in the range 0-1 in computing the velocity components at these three values of the cumulative distribution function.

Instantaneous physical properties for each eddy are found in a similar manner. The instantaneous mixture fraction is assumed to have a clipped Gaussian probability density function with mean value and variance equal to f and g . The cumulative distribution function is constructed for this PDF and a single random number selection in the range 0-1 yields the instantaneous mixture fraction of the eddy at the sample value of the cumulative distribution function. The state relationships then provide the physical properties of the eddy at this mixture fraction. In this case state relationships are formed allowing only for the mixture fraction of the gas phase.

A particle is assumed to interact with an eddy for a time which is the minimum of either the eddy lifetime or the transit time required for the particle to cross the eddy. These times are estimated using the dissipation length scale and velocity fluctuation of the eddies. These parameters can be found directly from the k-e-g model of the continuous phase.

The remainder of the computation proceeds similar to the deterministic separated flow model. The only change is that the source terms are computed for the random-walk trajectories of the particles as opposed to their deterministic solution. The main disadvantage of the stochastic method is that more particle trajectories must be considered in order to obtain statistically significant particle properties.

The stochastic model yields estimates of both mean and fluctuating particle properties at each point in the flow. This information is useful, since these properties can be measured and provide a good test of model performance. A notable feature of the model is that added empiricism is minimal--in fact, no new constants must formally be prescribed.

Preliminary evaluation of the SSF model is described in Refs. 3-6. Various particle-laden flows were examined in order to minimize complications due to particle coalescence. The data base included flows in channels as well as particle-laden jets, cf. Refs. 11-18. Comparison between predictions and measurements was very encouraging. However, uncertainties in initial conditions for many of the jet flows limited the thoroughness of this evaluation.

3. Experimental Methods

3.1 Test Facility

A sketch of the test apparatus used for both particle-laden jets

and sprays appears in Figure 1. The present flows all have densities greater than air; therefore, the jet exit is directed downward in still air in order to avoid recirculation. Some of the measurements employ optical instrumentation which must be mounted on a rigid base. Therefore, probing the flow is accomplished by traversing the jet exit or injector in three dimensions.

The flow is protected from room disturbances using a screened enclosure (1 m square by 2.5 m high). Major traversing, to obtain radial profiles of flow quantities, involves moving the entire cage assembly. This keeps the flow nearly concentric with the vertical axis of the cage.

The inlet to the exhaust system is screened and is located 1 m below the plane of instrumentation. Testing has shown that operation of the exhaust system has a negligible effect on flow properties at the measuring position.

3.2 Particle-Laden Jet

A sketch of the flow system arrangement for the particle-laden jet experiments is illustrated in Figure 2. The jet tube has an internal diameter of 4 mm and extends in the vertical direction for 100 injector diameters. Flow at the exit of the injector roughly corresponds to fully-developed turbulent flow, however, the initial condition is completely measured in any event.

The air supply for the particle-laden jet apparatus is provided by an oil-free air compressor. The air flow is metered using a critical flow orifice. Seeding particles needed for operation of the laser-Doppler anemometer are added using a reverse-cyclone seeder. The flow then passes to an NBS particle generator where the larger particles for the two-phase flow are added. The flow then passes to the injector tube, which is over 100 diameters long, and yields a nearly fully-developed flow at its exit. The injector tube is capable of a three-dimensional traverse, since optical components are fixed. Conditions at the exit of the injector tube are measured directly in order to define initial conditions for the flow.

Test conditions include three different particle sizes and several loading ratios (loading ratio is the mass of particles per unit mass of air in the injector exit flow). The particles were sifted yielding a relatively monodisperse size for each size considered.

3.3 Evaporating Spray Tests

The sketch of the flow system for the evaporating spray experiments appears in Figure 3. The flow system is similar to that employed for nonevaporating spray tests in the initial phases of this investigation [3,6].

A Spraying Systems Company Air-Atomizing Injector (Model 1/4J2050 Fluid Nozzle and 67147 Air Nozzle with outlet diameter of 1.19 mm) is used for the evaporating spray tests. The air side of the injector flow is filtered and metered with a critical flow orifice. The same air supply is tapped to provide tank pressurization for the liquid flow to the injector.

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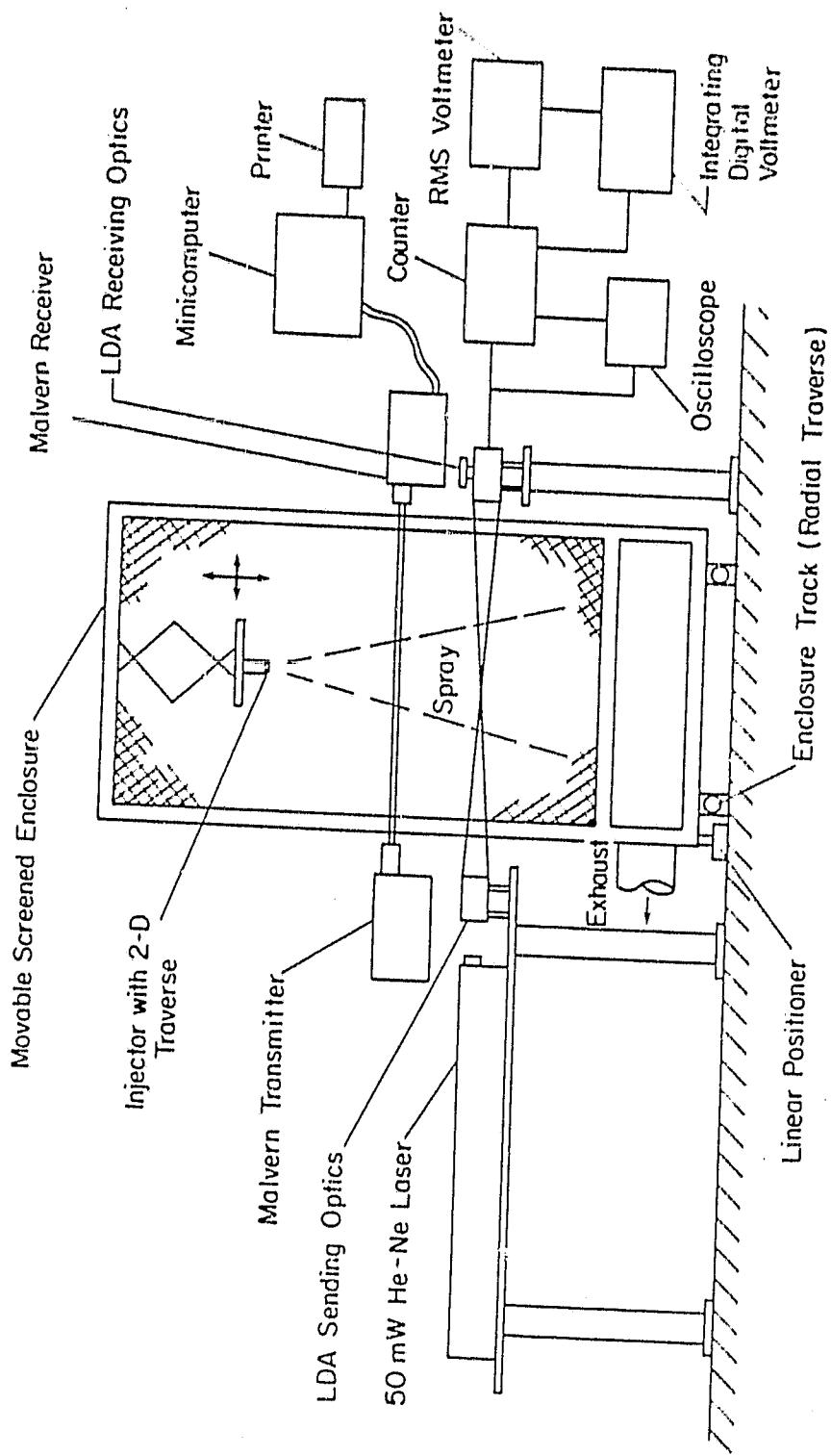


Fig. 1. Sketch of the spray apparatus.

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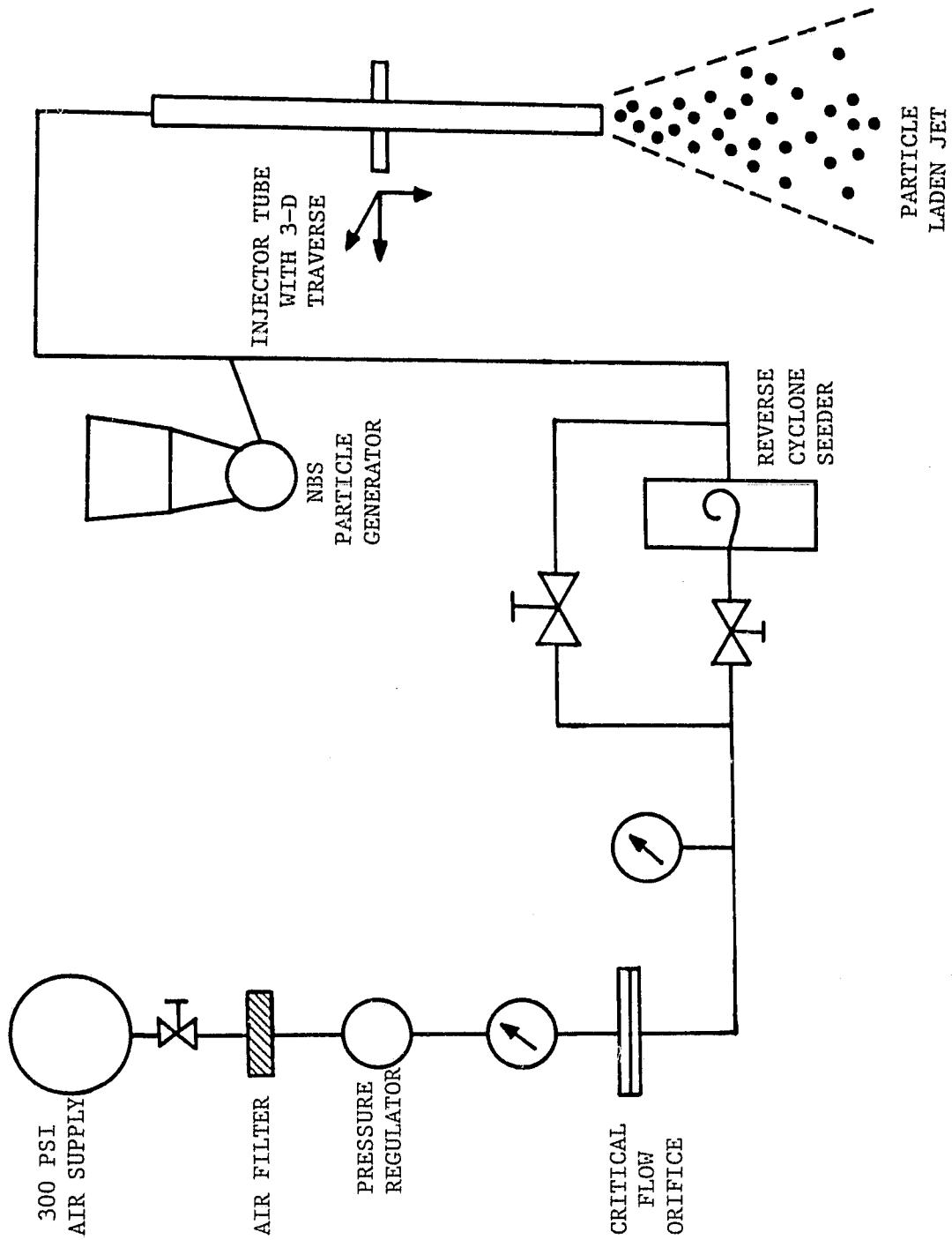


Fig. 2. Sketch of the flow system for the particle-laden jet experiments.

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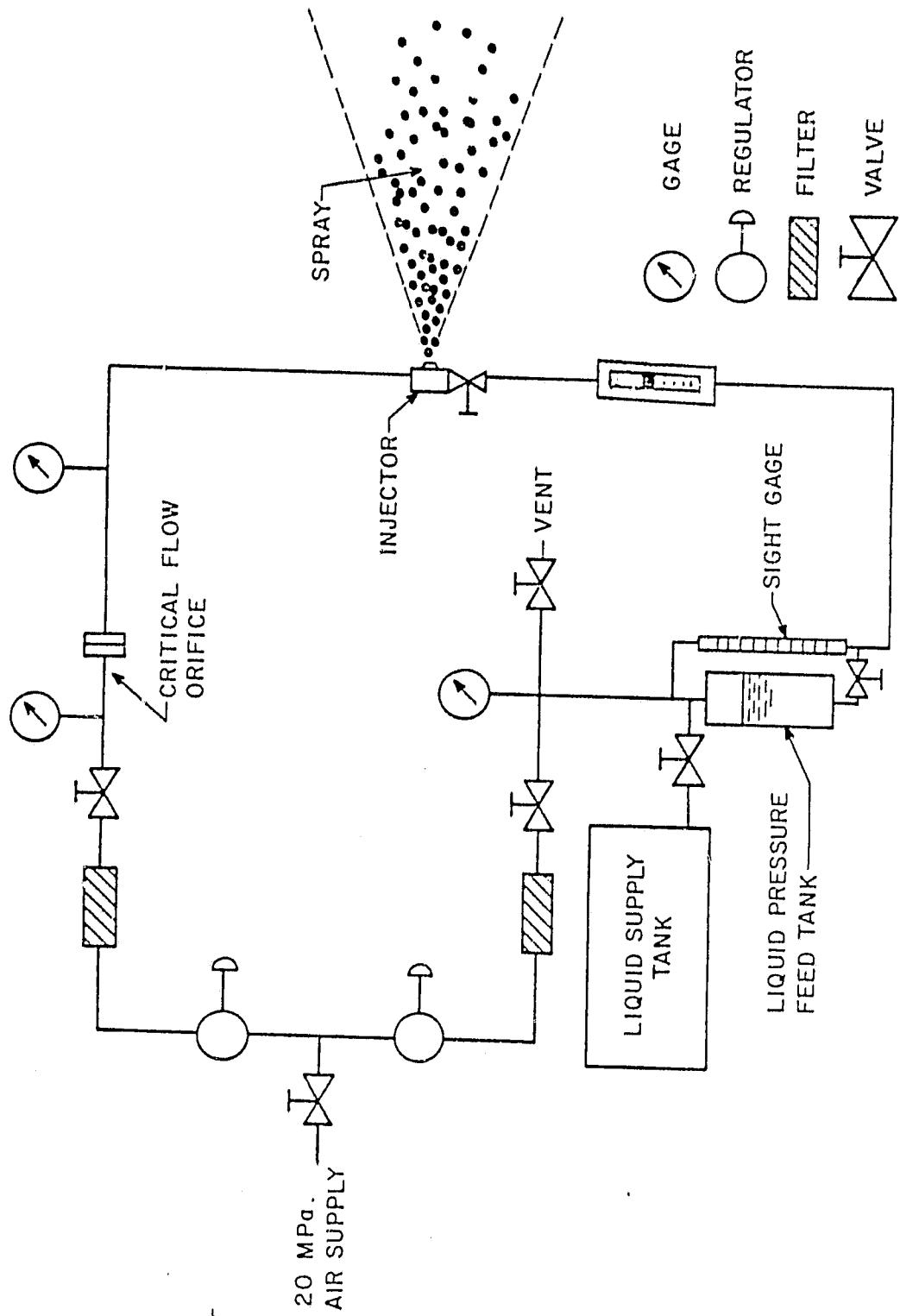


Fig. 3. Sketch of the injector flow system.

The liquid, Freon 11, is stored in a tank under pressure. The tank is not agitated and pressure levels are moderate; therefore, the dissolved air content of the liquid is negligible. The liquid-flow rate is controlled with a valve and metered with a rotameter.

Two sprays were considered in the tests. One spray involved flow conditions adjusted to provide a finely atomized spray having a SMD of 30 microns, which is similar to the spray studied earlier in this laboratory [7]. A second spray having SMD of roughly 80 microns is also being investigated in order to consider flows where velocity slip between the phases is more important.

3.4 Instrumentation

A laser-Doppler anemometer is used to measure mean and fluctuating gas velocities. Several beam orientations provide measurements of various velocity components as well as the Reynolds stress. To avoid problems of fringe bias and reverse flows, the laser beams are frequency-shifted. Concentration biasing and effects of drops or particles are avoided by employing high concentrations of seeding particles. Data processing also includes an amplitude limiter which prevents large particles from influencing measurements.

The laser-Doppler anemometer is also being used to measure particle velocity in the particle-laden jet experiments. In this case, the gain of the photodetector is set to relatively low levels so that only strong scattering signals from large particles are recorded. The output of the data processor is then collected with a MINC 11/23 minicomputer and processed to yield mean and fluctuating particle velocities (by taking particle-averaged velocities). When these tests are run, no seeding is used for the gas phase, in order to reduce potential bias errors for the measurements.

Determination of initial conditions for the evaporating sprays requires simultaneous measurements of particle size and velocity distributions. In order to obtain adequate spatial resolution, these measurements are undertaken at a position 50 injector diameters downstream from the injector exit. This point corresponds to the same condition where gas-phase initial condition measurements were made. In order to insure that initial conditions were defined reliably, a double-flash photography technique was employed. This involves photographing the flow under high magnification using two short-duration flashes separated by a known and controllable time interval. While the technique is tedious, since numerous photographs must be analyzed in order to obtain statistically-significant data, it is reliable--even in a variable density flow having high particle loadings. The double-flash measurements were also used to verify laser-Doppler anemometer measurements of particle velocities in the particle-laden jet experiments.

Particle mass velocities were obtained by isokinetic sampling. Particles passing into the sampling probe were collected on a filter and weighed after a timed period of collection in order to determine their mass flux.

The mean composition of injected fluid in the evaporating sprays was also determined by isokinetic sampling--at the mean-gas velocity. The probe used for this purpose is illustrated in Figure 4. This involves a constant diameter probe having an inside diameter of 4 mm. The probe tip was heated, using an electrical coil, for a distance of 20 mm. This causes all the liquid material in the flow to evaporate. The resulting gas mixture is then analyzed with a gas chromatograph. This provides a direct measurement of the local mixture fraction of the flow. The system used is identical to Shearer et al. [7].

It is difficult to obtain accurate mean temperature measurements in the evaporating sprays due to effects of drop impaction. A shielded temperature probe was employed for present tests to reduce effects of drop impacts. This probe is illustrated in Figure 5. The probe involves a fine-wire thermocouple stretched along the centerline of a small tube. The portion of the tube near the thermocouple junction is cut away so that the thermocouple can be exposed to gas flow. By placing the shielded portion of the probe upstream in the flow, drop impacts directly on the junction can be avoided. Throughout present tests this probe was only marginally successful and it is felt that temperature measurements in the evaporating spray are only of qualitative significance in the region where two-phase flow was encountered.

4. Results and Discussion

4.1 Particle-Laden Jets

All testing and data reduction has been completed for the particle-laden jets. Thus far, the measurements have been compared with predictions of the SSF model. Subsequent comparison between predictions and measurements will include the locally homogeneous flow model as well. Since final figures are still being prepared, only a portion of the results will be considered in the following in order to indicate the general nature of the findings. Thus, the following results will be limited to flow having particles with an SMD of 79 microns at a loading ratio of 0.2.

Figure 6 is an illustration of predicted (SSF model) and measured particle and gas velocities along the axis of the jet. Since this flow leaves the injector tube as a nearly fully-developed flow, there is no potential core and gas velocities begin their decay along the centerline right at the injector exit. Due to particle inertia, however, the rate of decay of particle velocity is smaller than the gas velocity. This results in significant slip between the phases for values of x/d greater than 10. The comparison between predictions and measurements is seen to be quite satisfactory.

Figure 7 is an illustration of predicted and measured mean particle mass velocities along the axis of the particle-laden jet. This parameter provides an indication of particle concentration predictions of the theory. It is evident from the results illustrated that the model yields excellent predictions of particle mass velocities.

Figures 8 and 9 are illustrations of predicted and measured particle and gas velocities as a function of radial distance for stations located 20

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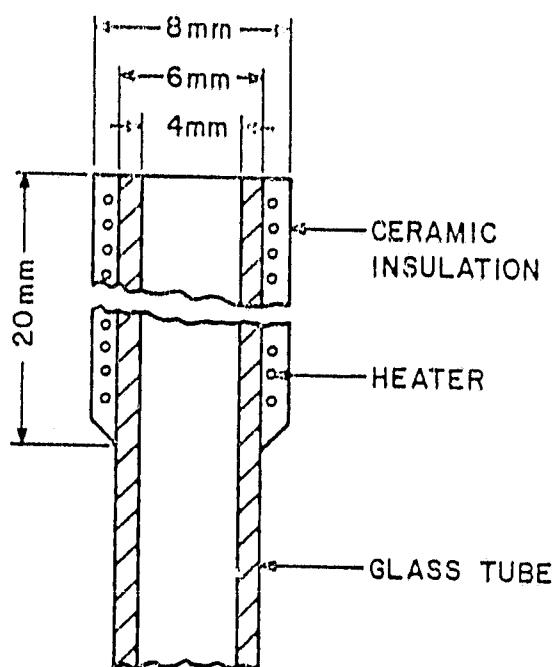


Fig 4. Sketch of the Sampling Probe

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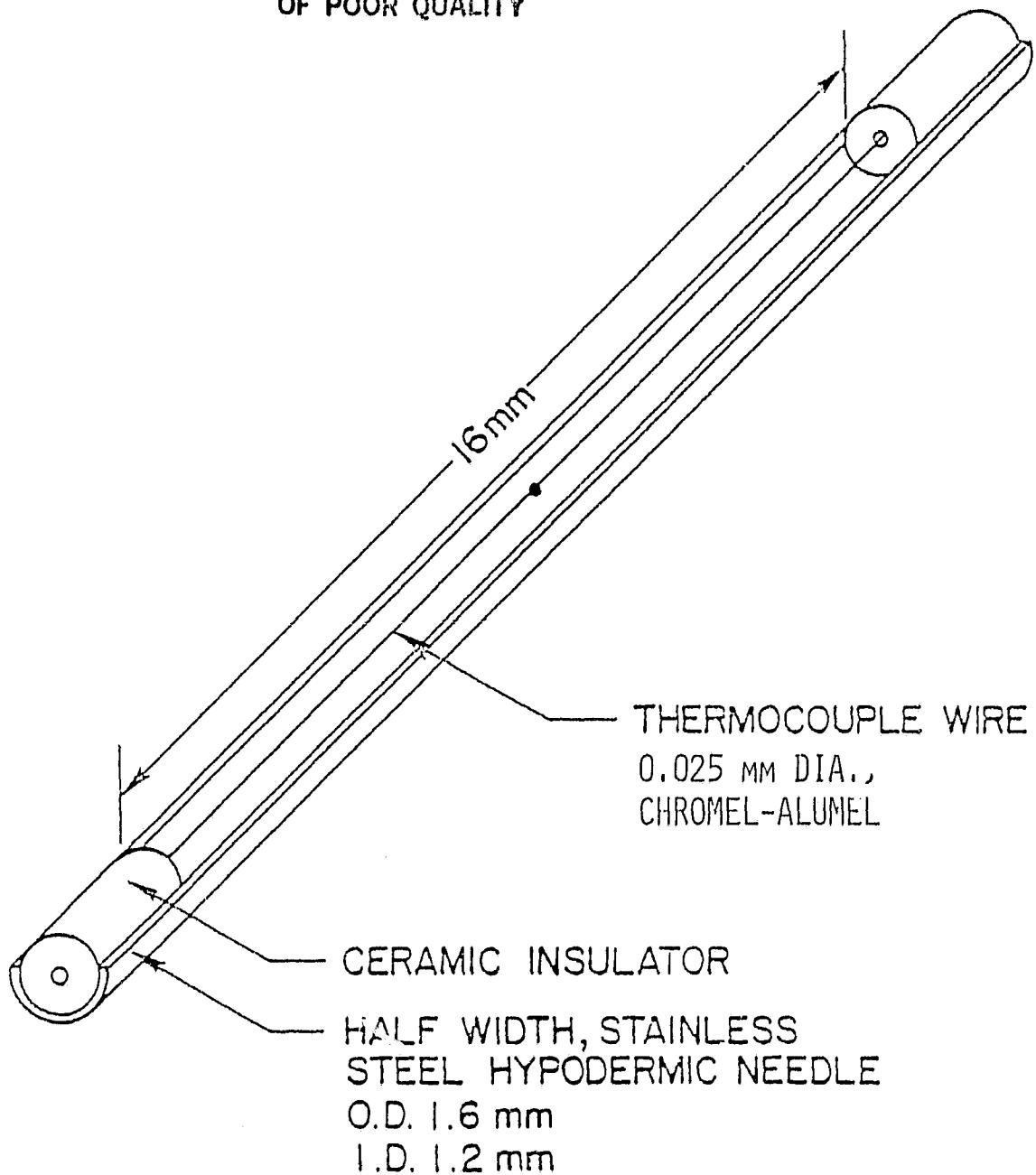


Fig 5. Sketch of the Spray Temperature Probe.

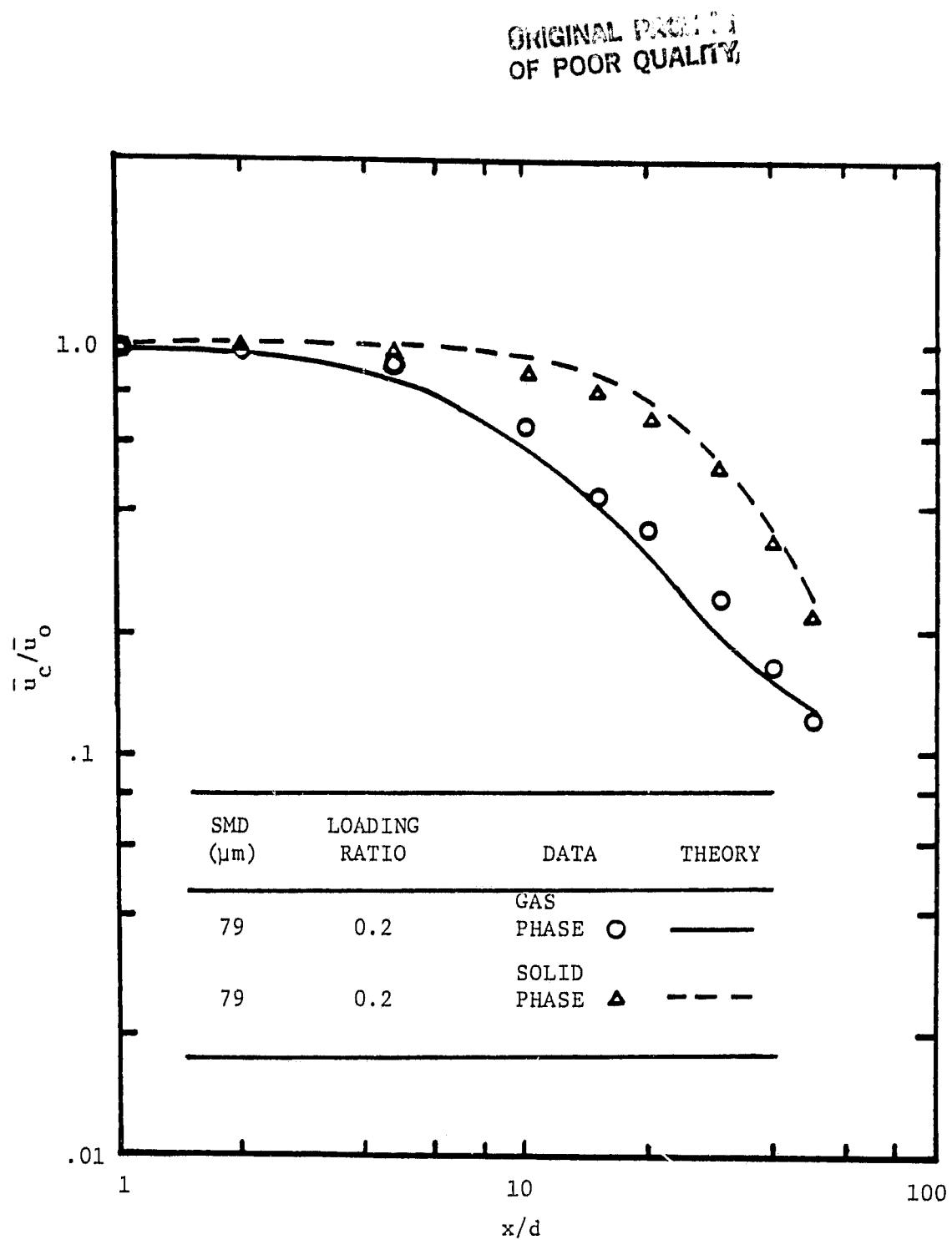


Fig. 6. Gas and particle mean velocities along the axis of the particle-laden jet (SMD = 79 microns).

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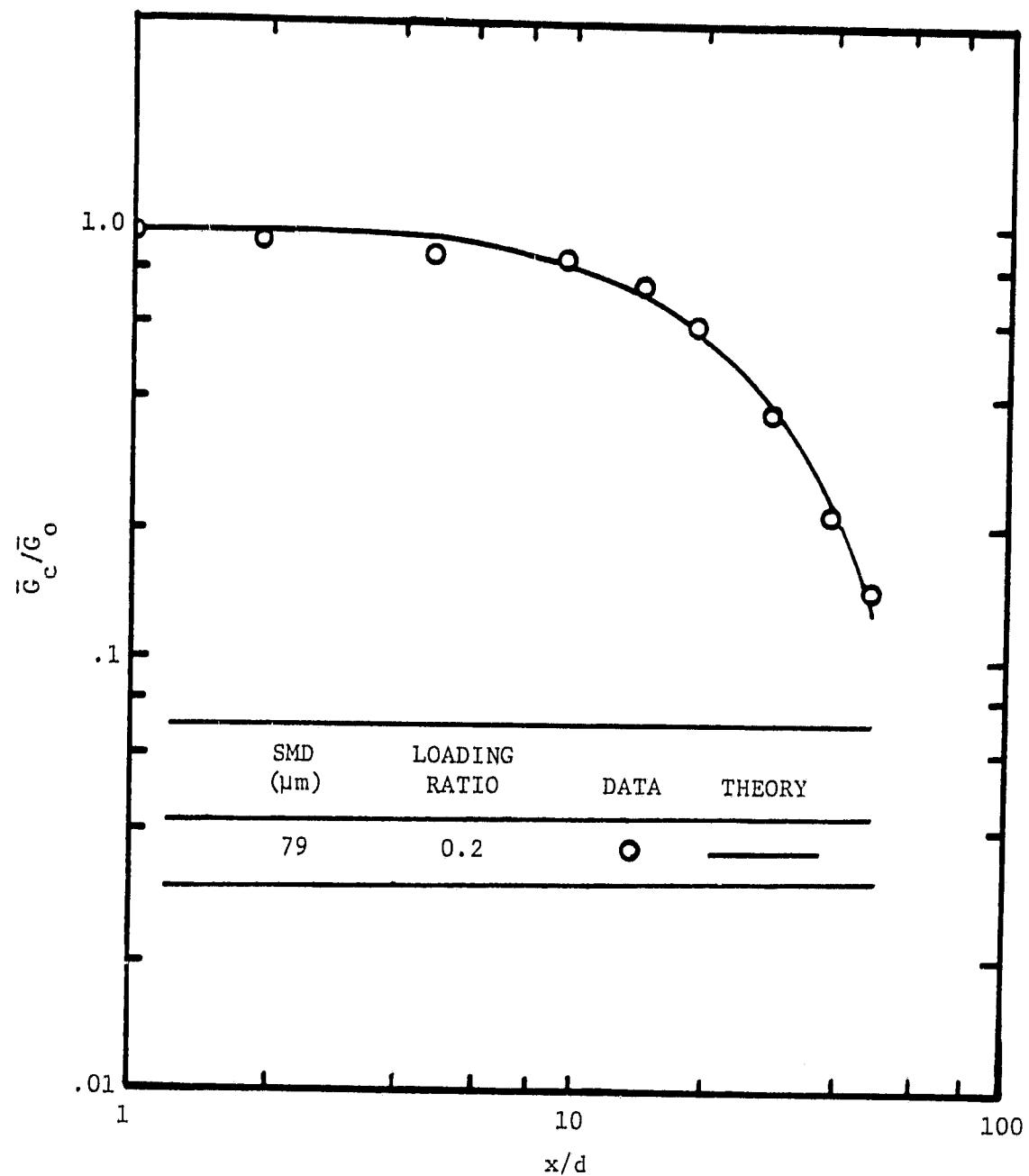


Fig. 7. Mean particle mass velocity along the axis of the particle-laden jet (SMD = 79 microns).

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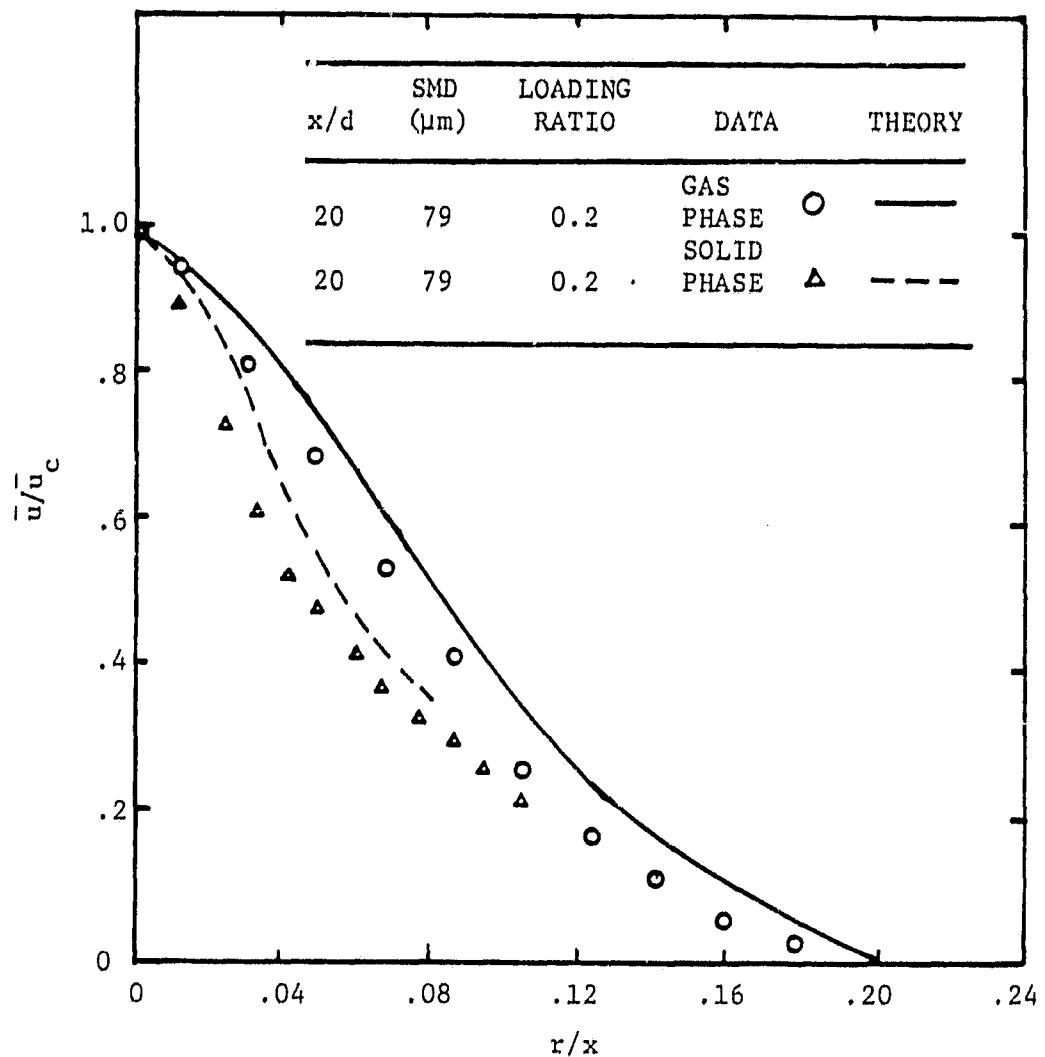


Fig. 8. Radial variation of mean gas and particle velocities in the particle-laden jet (SMD = 79 microns, $x/d = 20$).

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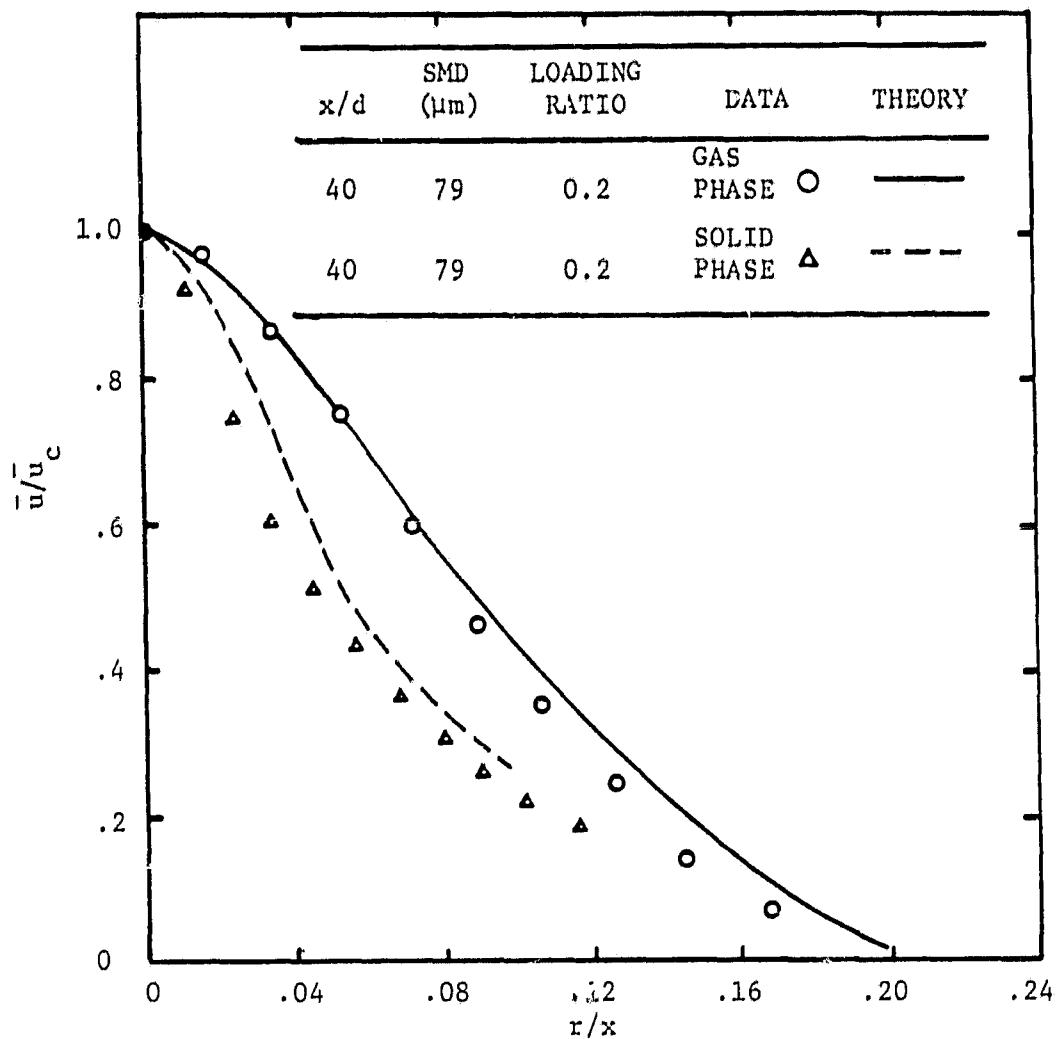


Fig. 9. Radial variation of mean gas and particle velocities in the particle-laden jet (SMD = 79 microns, $x/d = 40$).

and 40 injector diameters from the jet exit. Radial distances have been normalized by the axial distance from the injector exit in order to provide an indication of capabilities for predicting flow widths. Velocities have been normalized in terms of the centerline velocity of each phase. It should be recalled, cf. Figure 6, that centerline particle velocities at these stations are substantially greater than centerline gas velocities. Particle velocity determinations were terminated at $r/x = 0.10$, since particle concentrations were very low outside this region and would require excessively long times in order to develop velocity data. In general, the comparison between predicted and measured velocities of both phases is reasonably good.

Figures 10 and 11 are illustrations of predicted and measured particle mass velocities as a function of radial distance for axial stations 20 and 40 injector diameters from the injector exit. Variables are normalized on these figures similar to Figures 8 and 9. The comparison between predictions and measurements is seen to be excellent.

The results illustrated in Figures 6-11 are reasonably representative of the performance of the SSF model over the range of the new data. These results are most encouraging and continue to indicate that the stochastic model provides a reasonable representation of effects of turbulent dispersion of particles. These test flows are rather dilute, with void fractions in excess of 99%. Therefore, effects of turbulence modulation are probably small in these flows. Computations will be undertaken during the next report period in order to provide a more quantitative indication of potential influence of turbulence modulation on the comparison between predictions and measurements. There are still uncertainties with respect to particle size, since a narrow range of sizes was actually tested, and particle drag characteristics. Potential effects of these parameters on the comparison between predictions and measurements will also be examined during the next report period. Finally, sensitivity with respect to variations in initial conditions as well as the empirical parameters of the model will also be examined. Once these calculations and the complete comparison between predictions and measurements are completed, this phase of the investigation can be concluded.

4.2 Evaporating Sprays

Measurements of mean and fluctuating velocities of the continuous phase and mean mixture fraction were completed in the evaporating sprays. The test results available thus far are sufficient to evaluate the locally homogeneous flow model of the process; therefore, only this version of the models will be considered in the following.

Figure 12 is an illustration of predicted (LHF) and measured mean gas velocities along the axis of the evaporating sprays. The spray having an SMD of 30 microns is very similar to the spray considered by Shearer et al. [7]. The comparison between present predictions and measurements for this spray are also similar to the findings of Ref. 7. In the region downstream of the potential core, the velocity of the gas lags the predictions of the theory. The comparison between predictions and measurements deteriorates even further when the spray having the larger SMD is considered. Based on experience with nonevaporating sprays during the initial phase of this

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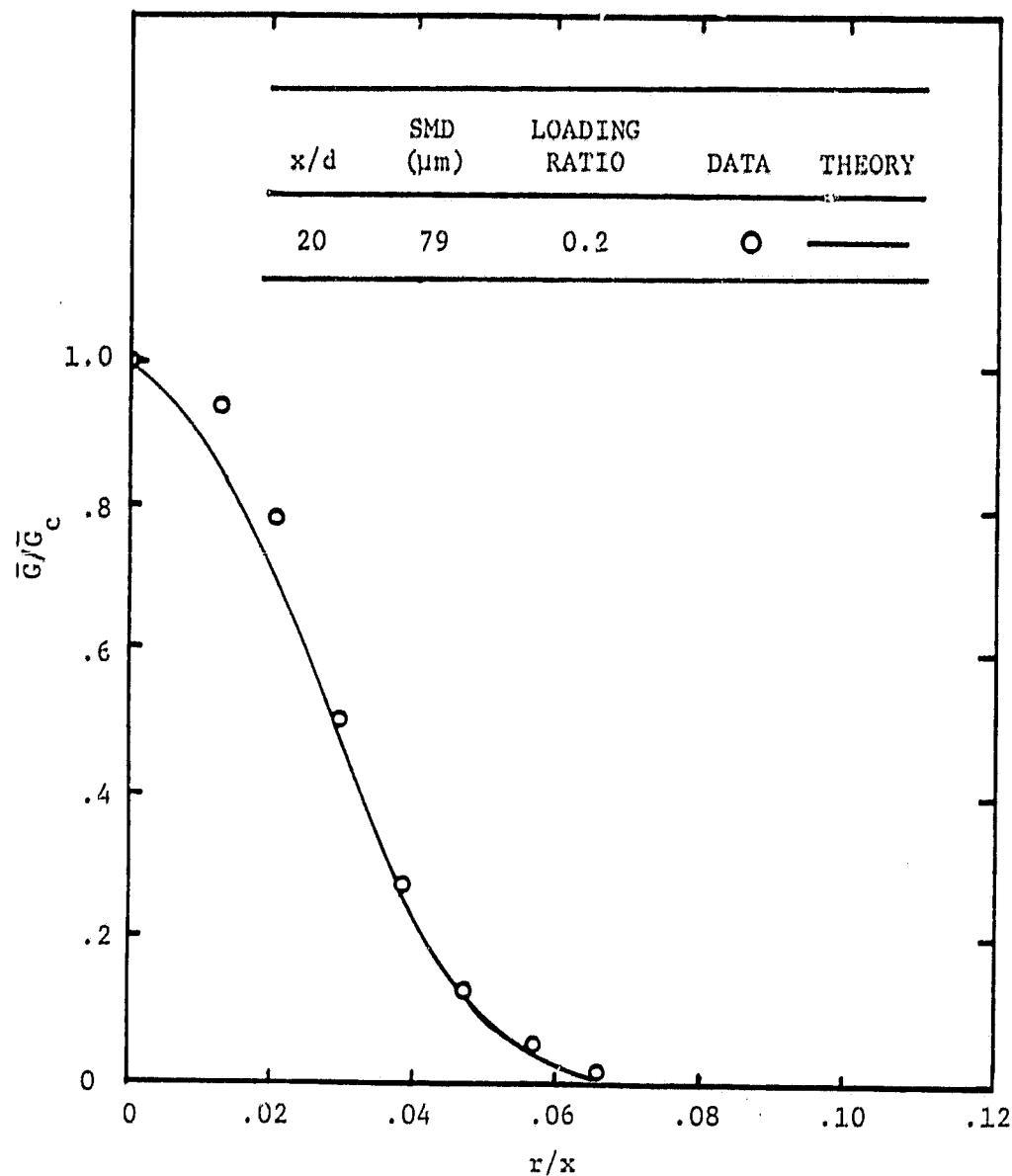


Fig. 10. Radial variation of mean particle mass velocity in the particle-laden jet (SMD = 79 microns, $x/d = 20$).

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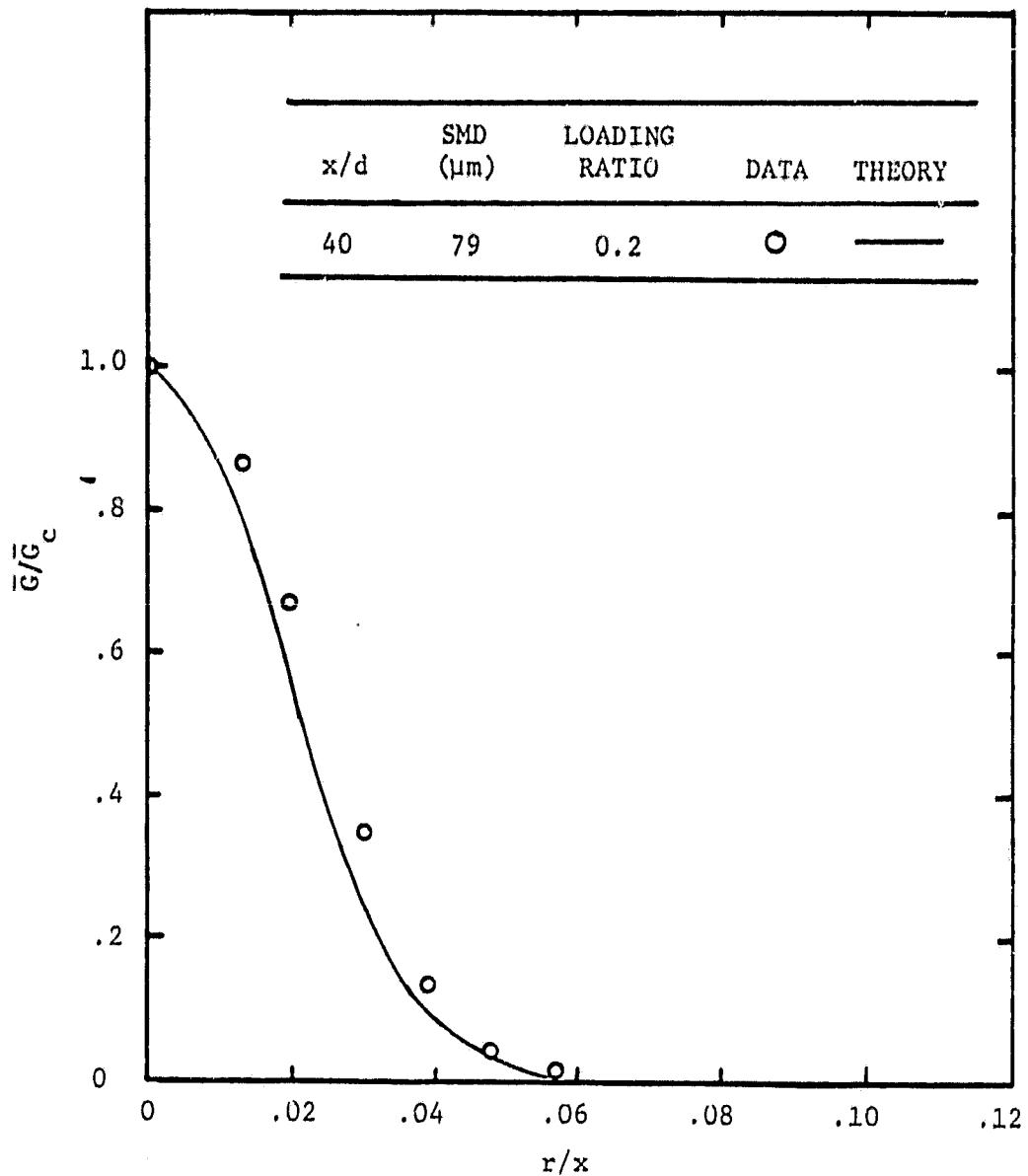


Fig. 11. Radial variation of mean particle mass velocity in the particle-laden jet (SMD = 79 microns, $x/d = 40$).

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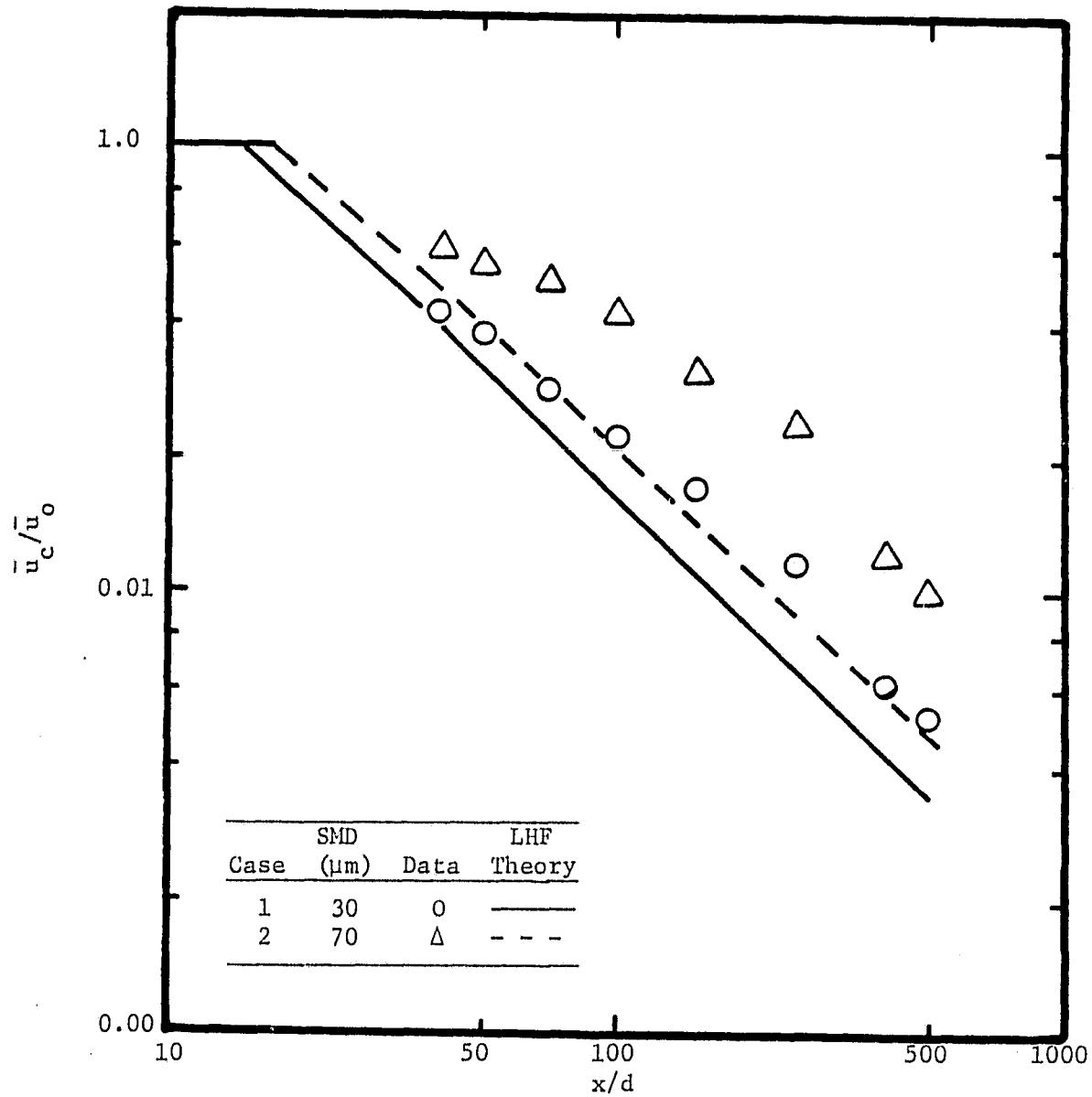


Fig. 12. Predicted and measured mean gas phase velocity along the axis of the evaporating sprays.

investigation, we would expect that the SSF model would rectify much of this deficiency.

Figure 13 is an illustration of predicted and measured mean mixture fractions along the axis of the evaporating sprays. As before, predictions are shown for the locally homogeneous flow model. The predictions for the spray having the smaller SMD are in fair agreement with measurements in the region far from the injector-- x/d greater than 200. Results for the larger diameter spray, however, are relatively poor throughout the range considered in the figure. The locally homogeneous flow model does indicate the correct trend that mixture fraction decay is slower for the larger diameter spray. Unfortunately, quantitative agreement between predictions and measurements leaves much to be desired.

Figure 14 is an illustration of predicted and measured radial variation of mean gas velocities in the evaporating sprays. At larger distances from the injector the comparison between predictions and measurements, when plotted in the manner shown in Figure 14, is reasonably good. It should be recalled, however, that centerline velocity predictions at these positions are not particularly accurate. Nearer to the injector the measurements indicate a larger flow width than predicted by the locally homogeneous flow model. This is probably a manifestation of turbulent particle dispersion, which tends to increase flow widths in comparison to gas jets. Computations with the SSF model will be required in order to confirm this behavior.

Figure 15 is an illustration of predicted and measured radial variation of turbulence kinetic energy in the evaporating sprays. Predictions are in qualitative agreement with the measurements, however, there are significant errors in almost every region of flow.

Figure 16 is an illustration of predicted and measured radial variations of Reynolds stress in the evaporating sprays. The agreement between predictions and measurements is reasonably good far from the injector, where effects of slip between the phases becomes small. Results nearer the injector, however, are not very satisfactory.

Figure 17 is an illustration of predicted and measured radial variation of mean mixture fraction in the evaporating sprays. The comparison between predictions and measurements in this case is reasonably good. However, it should be recalled that centerline mixture fractions--which are used to normalize both predictions and measurements--do not agree very well, cf. Figure 13.

In order to apply the SSF model to this data initial conditions must still be developed at $x/d = 50$. Data that is needed includes particle size and velocity distributions as a function of radial distance. These measurements, as well as similar measurements for nonevaporating sprays, are currently in progress. Once these results are in hand, computations can proceed using the separated flow models.

5. Status and Plans for the Next Report Period

5.1 Particle-Laden Jets

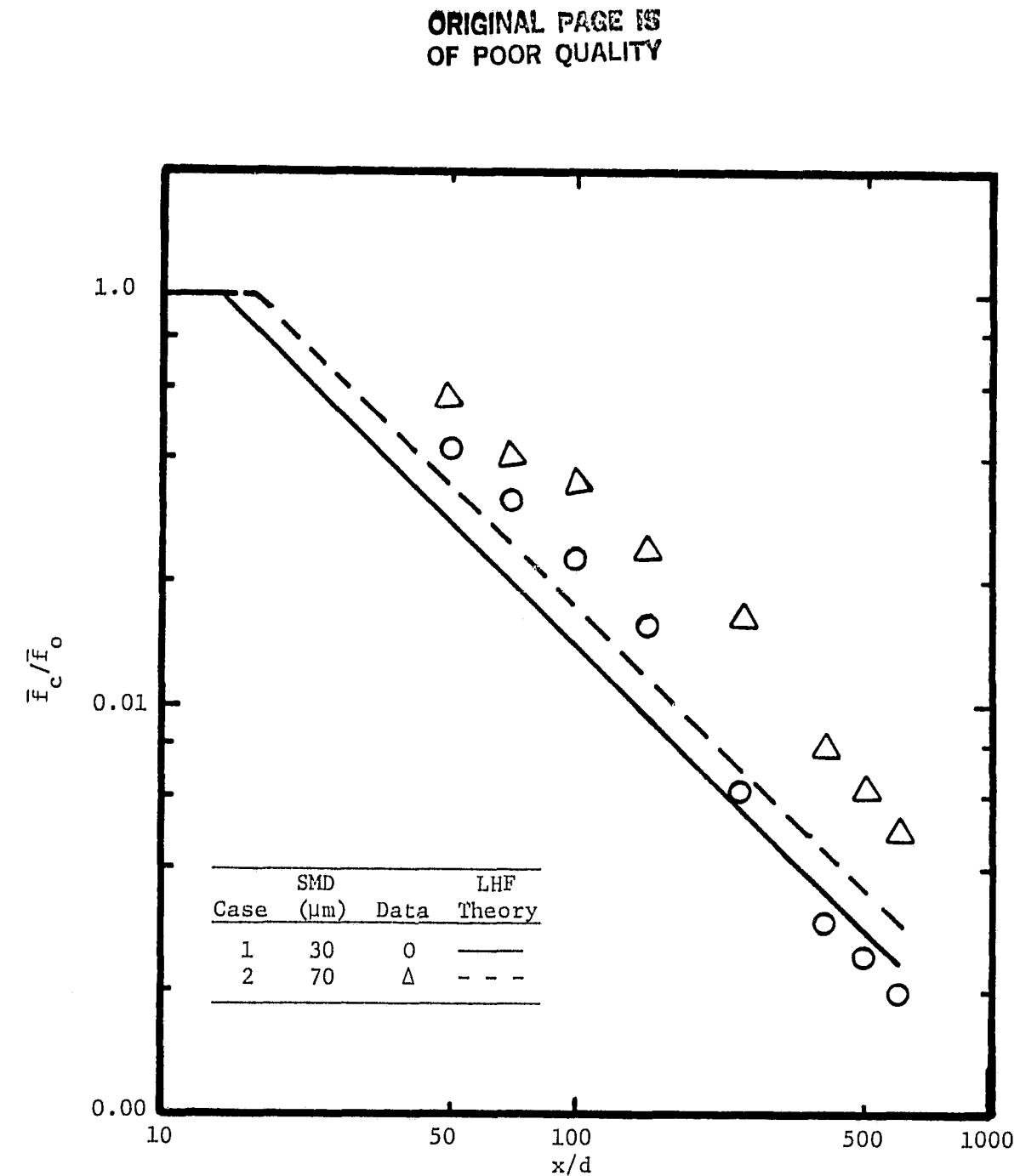


Fig. 13. Predicted and measured mean mixture fraction along the axis of the evaporating sprays.

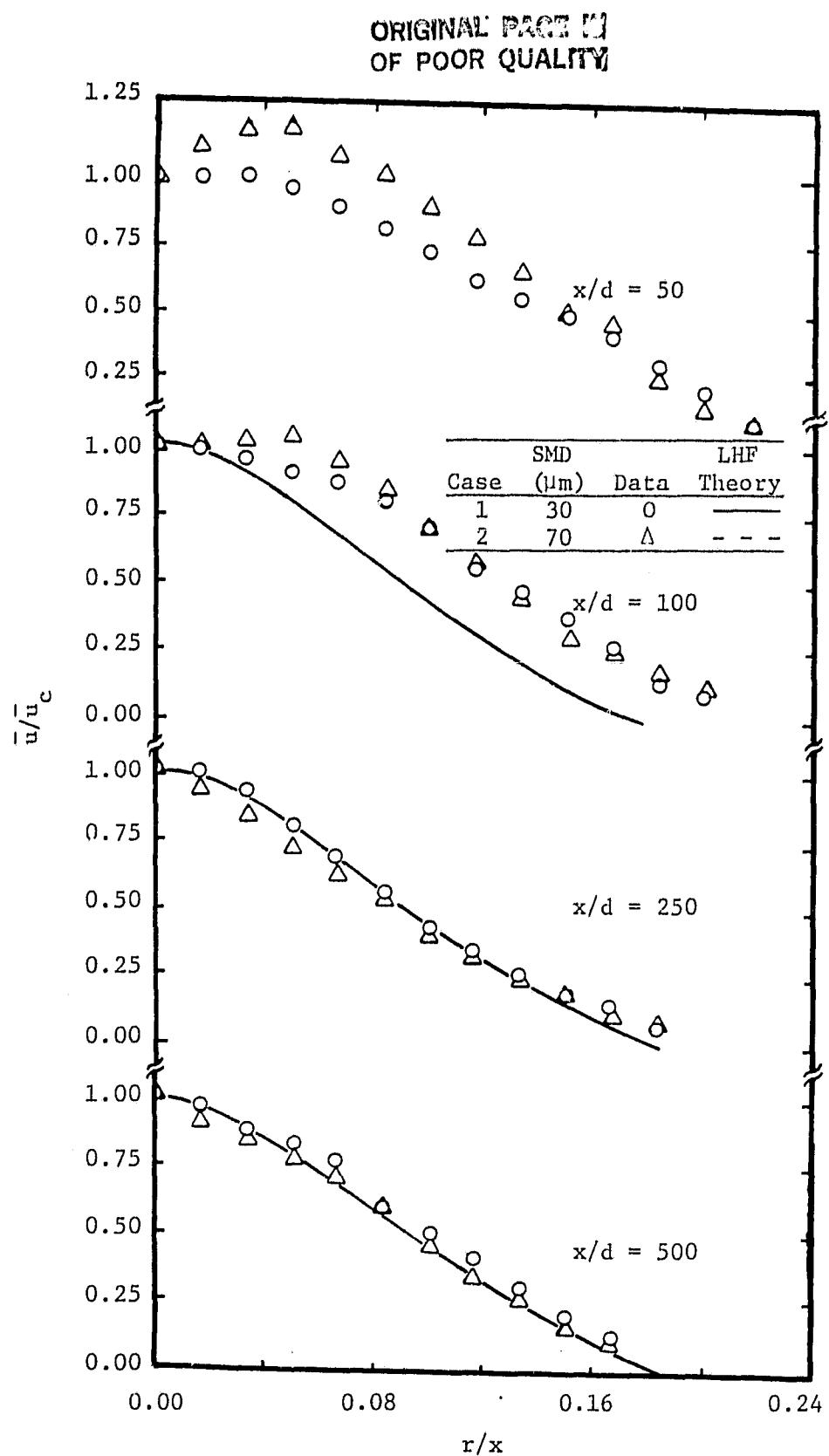


Fig. 14. Predicted and measured radial variation of mean gas velocity in the evaporating sprays.

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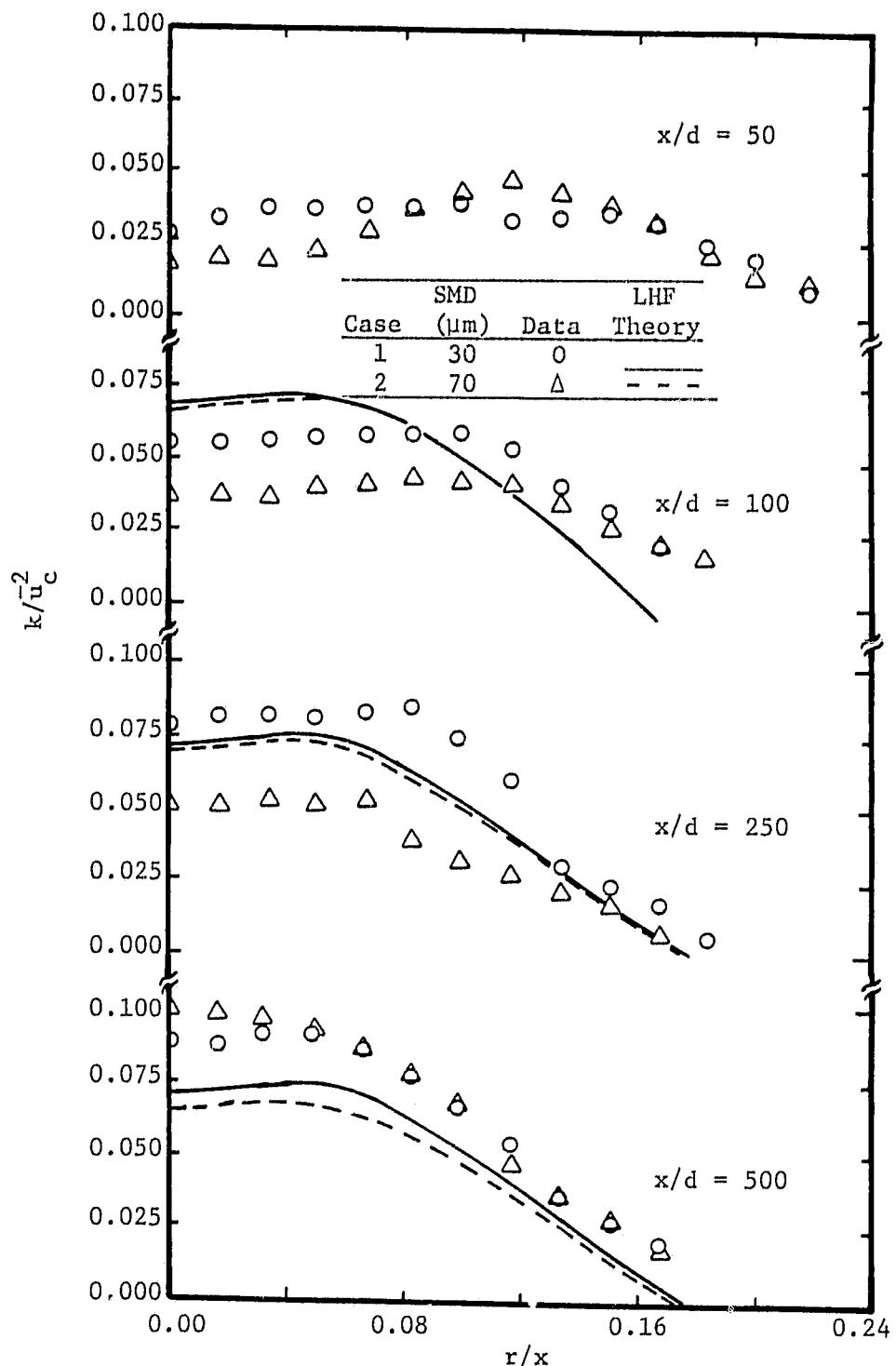


Fig. 15. Predicted and measured radial variation of turbulent kinetic energy in the evaporating sprays.

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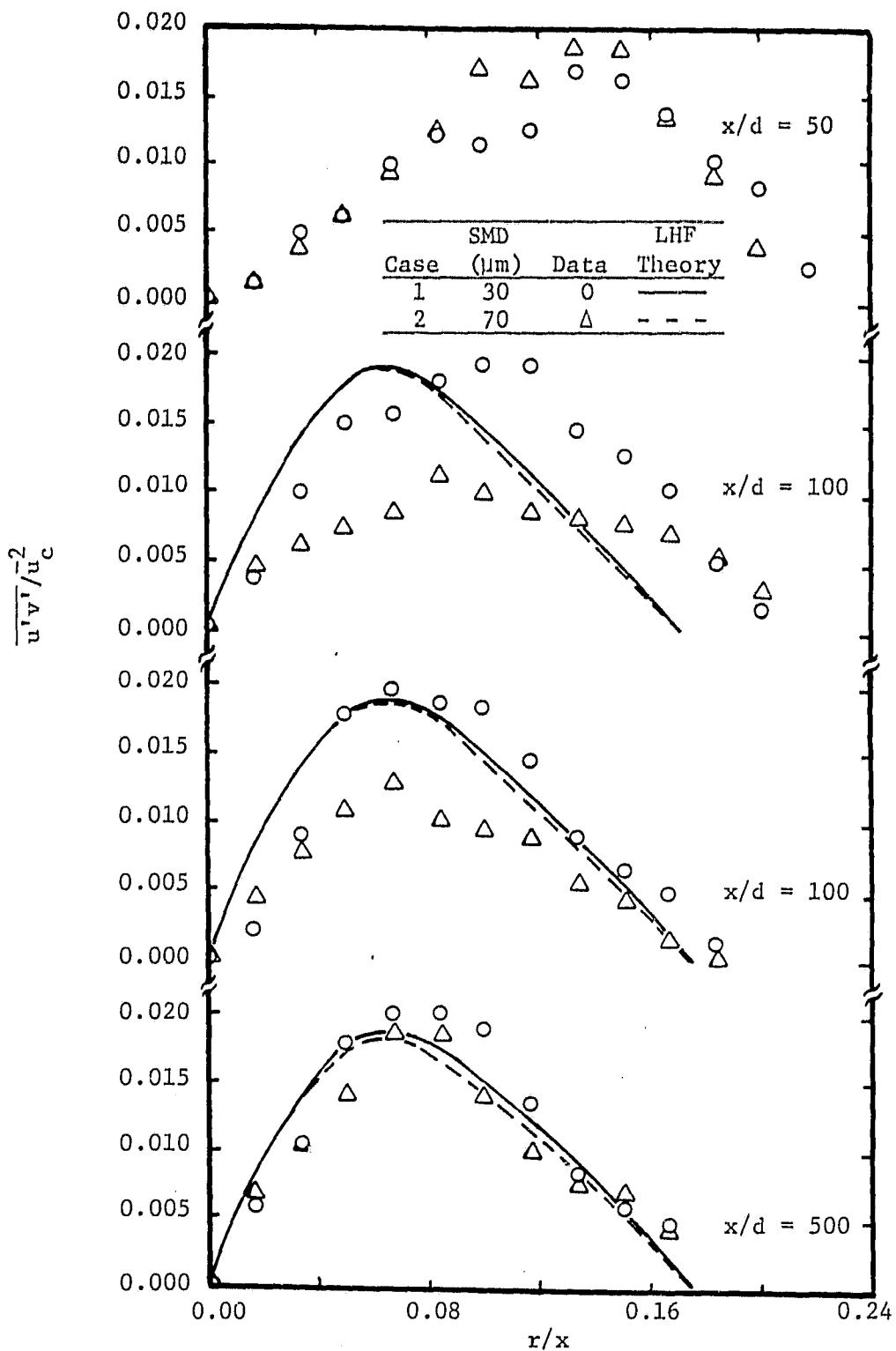


Fig. 16. Predicted and measured radial variation of Reynolds stress in the evaporating sprays.

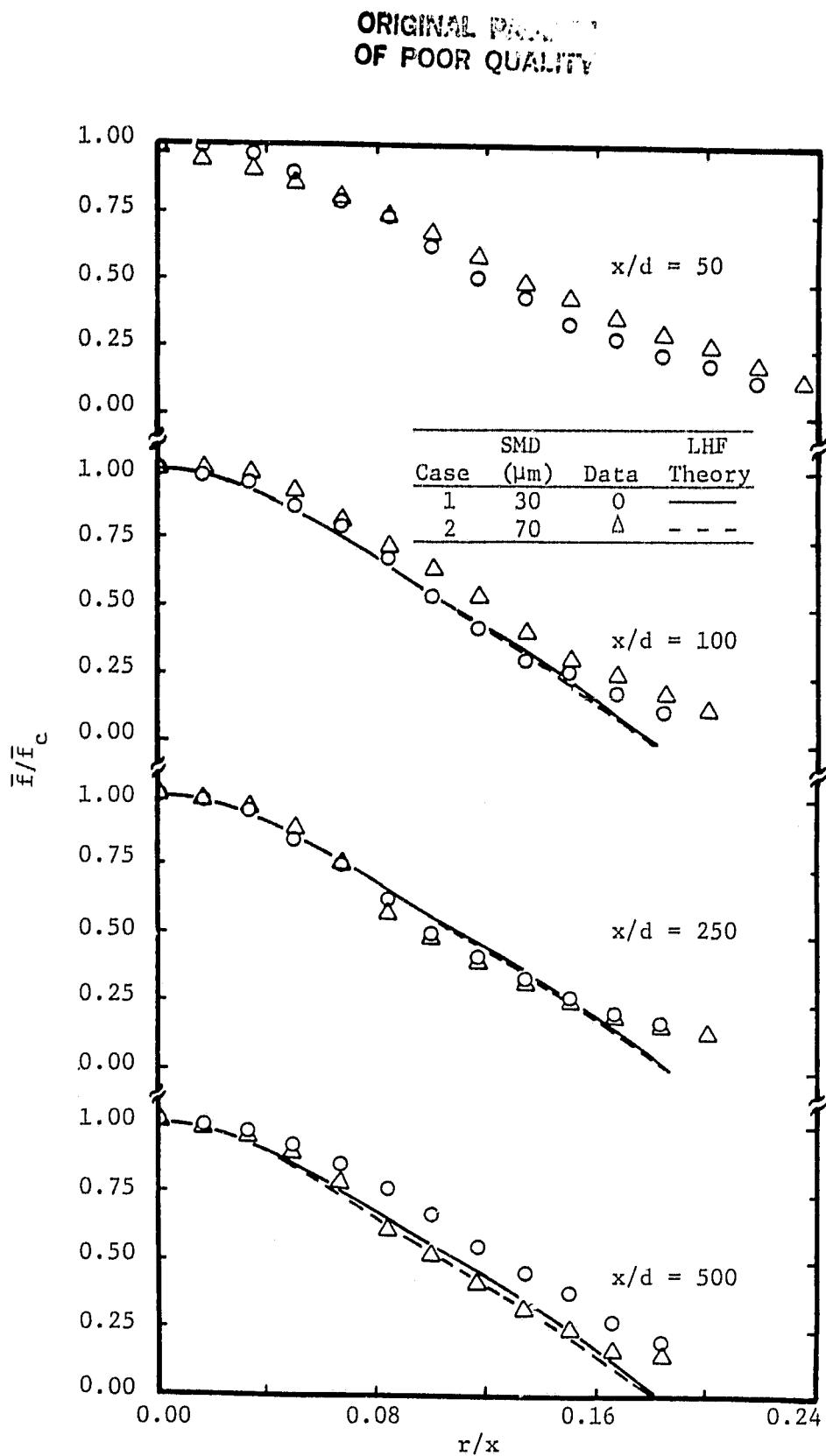


Fig. 17. Predicted and measured radial variation of mean mixture fraction in the evaporating sprays.

All experimentation for particle-laden jets has been completed. Information currently available is sufficient to complete comparisons between predictions and measurements for all three models. Computations have been completed for the SSF model, however, some sensitivity checks are in progress. Computations must also be undertaken LHF and DSF models as well. Based on past experience, Refs. 1-6, the DSF model will probably not be very effective. Therefore, computations with the DSF model will not be very extensive.

It is expected that all theoretical and experimental work for the particle-laden jets will be completed during the next report period. A report and papers describing these results will also be completed.

5.2 Sprays

Measurements for the nonevaporating and evaporating sprays have been completed, aside from determination of initial particle size and velocity distributions at $x/d = 50$. Tests are currently in progress to obtain this information using the double-flash photography technique. These tests are currently in progress, however, they are rather tedious since a rather large number of photographs must be obtained and a large number of particles must be counted. Nevertheless, it is expected that this information will be developed within the next few months.

Once initial conditions are adequately defined for both the nonevaporating and evaporating spray models, definitive separated flow computations can be made for these experiments. Computations will be completed using the deterministic separated flow and stochastic separated flow models. Similar to the particle-laden jet experiments, calculations will be also undertaken to determine the sensitivity of the predictions to variations in initial conditions, drag properties, and the empirical constants of the turbulence model. All results will be plotted and a report and papers describing the findings will be completed during the next report period.

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